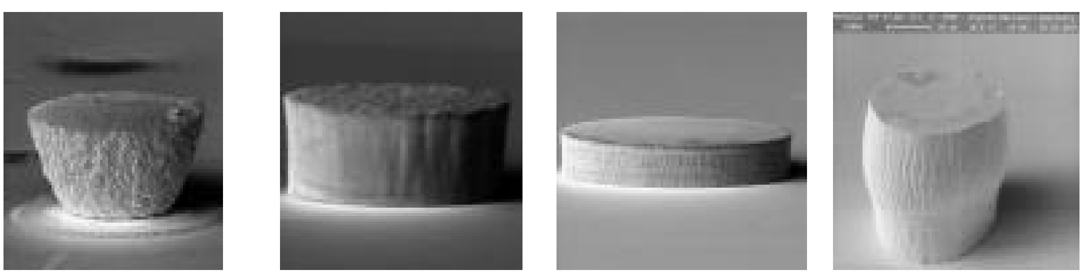
2.4 Microfabrication and Deep X–ray Lithography

2.4.1 Novel X-ray Optical Elements

Micromachining processes available in the recently commissioned microlithography cleanroom at the APS are becoming known in the users' community for their capabilities. We were successful in fabricating several x-ray optical components, such as beam stops, pinholes, microslits, orientation grids for microtomography, arrays of compound refractive x-ray focusing lenses, and collimation structures. Beam stops in the range from 10 to 80 μm diameter, and thickness from 15 to 45 μm were fabricated on top of silicon nitride membranes by optical lithography and thick photoresist technology followed by gold electroforming (Fig. 2.28). Similar techniques are used for fabricating pinholes with diameters of 1 to 10 μm.

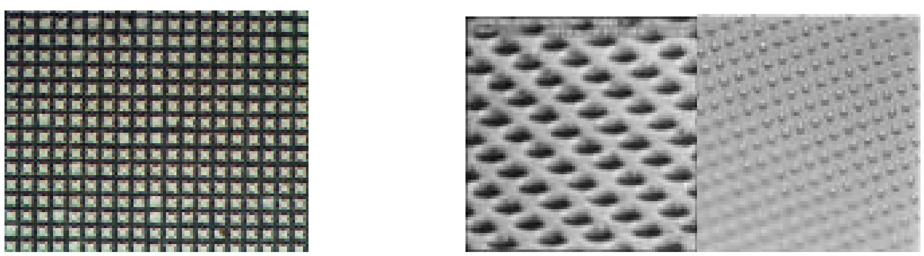


(a) (b) (c) (d)

Fig. 2.28. Scanning electron micrographs of beam stops of various dimensions. (a) D = 40 μm, h = 32 μm; (b) D = 40 μm, h = 20 μm; (c) D = 50 μm, h = 16 μm; and (d) D = 20 μm, h = 40 μm, where D is the diameter, h is the height of each structure.

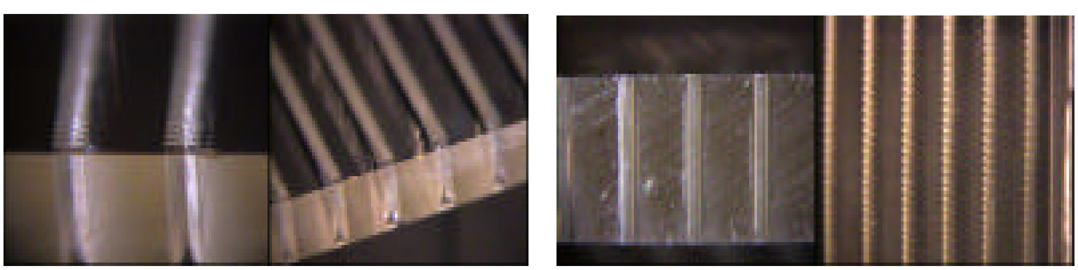
Orientation grids for x-ray tomography were made by optical lithography and electroforming on silicon nitride membranes (Fig. 2.29). Arrays of refractive compound focusing cylindrical lenses for hard x-rays were fabricated by deep x-ray lithography in polymethylmethacrylate (PMMA) plates of thickness from 1 to 6 mm (Fig. 2.30). The focusing distance has values between 2-5 m for the APS bending magnet beamline spectrum, and the lens aperture is 1 mm. Special effort has been made to decrease the roughness of the refractive structures and to control the exposure-induced deformation in PMMA (Moldovan, 1999). The focusing effect was tested and showed focusing capabilities in the 20-50 μm range for the x-ray spot size, limited mainly by the spherical aberration (Fig. 2.31). New arrays of parabolic lenses (under fabrication) are expected to reduce the spot size down to 0.5-5 μm.

Deep x-ray lithography, in conjunction with Au, Pb, Cu, or Pt electroforming, has been used for fabricating x-ray collimators. Preliminary tests showed capabilities of producing arrays of columns with 20:1 to 40:1 aspect ratios in 1-mm-thick PMMA (Fig. 2.32). These arrays will be used as electroforming molds for the collimators. As a result of a collaborative effort with NASA, the University of Melbourne, and Sandia National Laboratory, we have begun the fabrication of prototype structures for soft-x-ray lobster-eye lenses.



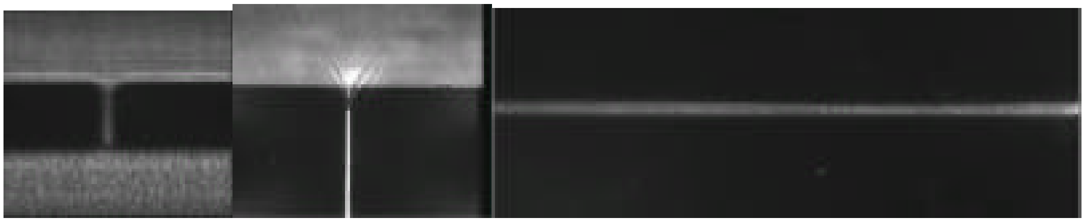
(a) (b)

Fig. 2.29. Arrays of gold squares and dots of various dimensions. (a) 4 μm pitch, 1 μm spacing and (b) 4 μm pitch, 1 μm diameter.



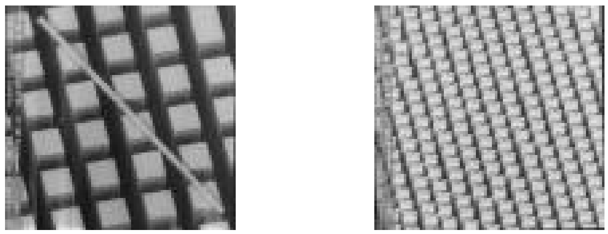
(a) (b)

Fig. 2.30. Arrays of cylindrical refractive lenses in (a) 3-mm-thick PMMA, and (b) 6-mm-thick PMMA.



(a) (b) (c)

Fig. 2.31. Focusing effect in a 1-mm-thick lens structure (a), in a 3-mm-thick structure (b), and along a 6-mm-high PMMA lens (c). The intensity in the upper half of (a) and (b) corresponds to the unfocused, direct 10 keV beam, passing above the lenses.



(a) (b)

Fig. 2.32. Arrays of columnar structures made of PMMA, prepared for electroforming x-ray collimators.

2.4.2 Zone Plate Fabrication by Focused Ion Beams

Fresnel zone plates (FZPs) are successfully used at APS beamlines to focus an x-ray beam to a submicron size. Currently x-ray FZPs were fabricated using a combination of electron-beam and x-ray lithography. New developments of FZPs concentrated on increasing the resolution and the efficiency, which means smaller linewidths and thicker zones, hence higher aspect ratios. For this reason, we investigated alternative fabrication methods. As a prototype, an x-ray zone plate was fabricated using the novel approach of focused ion beam (FIB) milling. A focused ion beam had been successfully used for x-ray mask repair and is an attractive tool for fabrication of high-aspect-ratio structures. During FIB milling, material is removed by the physical sputtering action of ion bombardment. The sputtering yield is high enough to remove a substantial amount of material. Therefore FIB milling provides a direct (maskless) patterning method with accuracy in the range of tens of nanometers. Using the 9500HT FIB station from Micrion, which has a 50 keV Ga^+ column, we succeeded in fabricating an x-ray phase zone plate (Fig. 2.33) with an aspect ratio of up to 6:1. Circular Fresnel zones were milled in a 1.0-μm-thick TaSiN film deposited on a silicon wafer. The outermost zone width of the zone plate is 170 nm at a radius of 60 μm. The time it took to mill each zone was about 90 s, and 70 zones were made. The electron micrograph shows that the zone plate structures are rather well defined. The focusing characteristics of this zone plate are being tested at 2-ID-D. In terms of achieving structures with an even higher aspect ratio, the beam profile and redeposition of the material during milling will need to be considered carefully.